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Ion Collection by a Positive Ion Mass Spectrometer

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13. ABSTRACT

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Abstract

Measurements of the voltage-current ion-collection characteristics of a rocket-borne quadrupole mass spectrometer are reported and compared with those previously obtained by means of numerical calculation.

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Ion Collection by a Positive Ion Mass Spectrometer

I. INTRODUCTION

The work described in this report is oriented towards obtaining a better understanding of the sampling procedure for our rocket-borne, electric quadrupole, positive-ion, mass spectrometer (Bailey and Narcisi, 1966). More specifically, the problem treated is that of assessing the role of electric fields in collecting ions from the ambient ionosphere. For our purposes, the flight instrument is considered to be an electrostatic probe, not a mass spectrometer, and the problem with which we are concerned is that of determining and interpreting the voltage-current characteristics of this probe.

Calculations of probe characteristics, including details of electric sheath formation are, in general, of a complicated nature. In the present case the difficulty is further increased by the geometry of our particular spectrometer housing which requires the use of two spatial coordinates to describe the space surrounding the probe. A set of calculations specifically made for the geometry of our instruments was recently completed by Parker (1970), and the results of these calculations are compared with probe characteristics obtained from one of our positive ion flights. This comparison, although based on data of only a single flight, will, hopefully, aid in determining the direction to take in future theoretical and experimental efforts.

(Received for publication 19 January 1972)

2. EXPERIMENTAL FLIGHT DATA

The flight from which this data was taken occurred during a polar cap absorption event, and was launched from the Fort Churchill, Manitoba, range on 3 November 1969 at 0730 U. T.

An outline of the spectrometer housing (which constitutes one electrode of the probe) and the payload body and second-stage motor (which together constitute the other) is shown in Figure 1. Probe characteristics are generated by a linear voltage ramp that in 0.5 sec sweeps the instrument housing from +5 to -20 V with respect to the vehicle body. A strip-chart segment showing two typical characteristics so generated is shown in Figure 2. The data presented in this report were taken from 50 such characteristics that occurred between the altitudes of 98 and 136 km. The upper limit is set by the (arbitrarily) imposed requirement that the angle of attack be less than 30 deg, and the lower limit by the requirement that water cluster ions, which may break up at higher sampling voltages (Burke et al, 1970; Narcisi, 1970), do not contribute to the total current.

The characteristics shown in Figure 2 were obtained while the quadrupole was operated in a total ion mode; each scan frame contains two characteristics: one for ions greater than 34 amu, and the other for ions greater than 50 amu. The ions that contribute to these characteristics are 56 amu (iron) and 40 amu (calcium). No attempt to correlate characteristics with vehicle angle of attack was made.

Limiting the angle of attack to less than 30 deg insures that the correction for such angles will be small; further, with 50 characteristics, any short-term variations in angle may be assumed to be statistically smoothed. A plot of the maximum current, I_{20} for each scan (that is, that at -20 V applied potential), versus altitude is shown in Figure 3.

For the most part, currents associated with ions of mass > 50 amu and > 34 amu seem to be equal within experimental error, indicating that the concentration of ions of mass 56 is much greater than that of ions of mass 40. This is compatible with previous results obtained in the scanned mode. Below 110 km, however, there are three points for which the current for ions > 34 amu seems to be greater than that of the current for ions > 50 amu. This would correspond to a substantial fraction of the total ions being of mass 40 amu, a result incompatible with scanned mode data and at present not understood.

Data are reduced as follows. To eliminate visible noise, a smooth curve is drawn by eye through each probe characteristic. This curve is then sampled at the five points corresponding to draw-in voltages of 0, 5, 10, 15, and 20 V. Two significant aspects of the data are then chosen for presentation. The first of these, I_{20}/I_0, is the ratio of current collected at -20 V to that collected at zero volts; that is, the maximum current collected normalized to the field-free current.

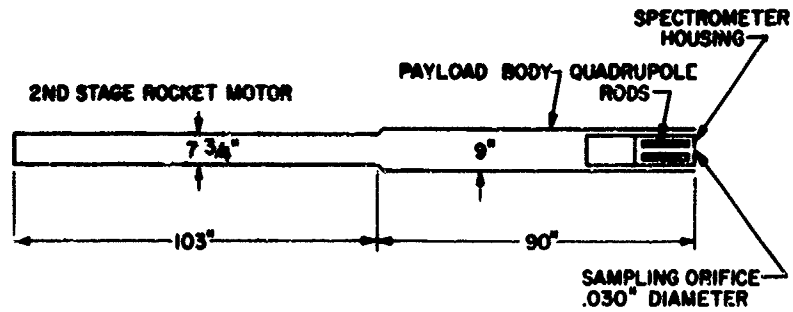

Figure 1. Outline of Spectrometer Housing and "Ground Return" Consisting of Payload Body and Second State Rocket Motor

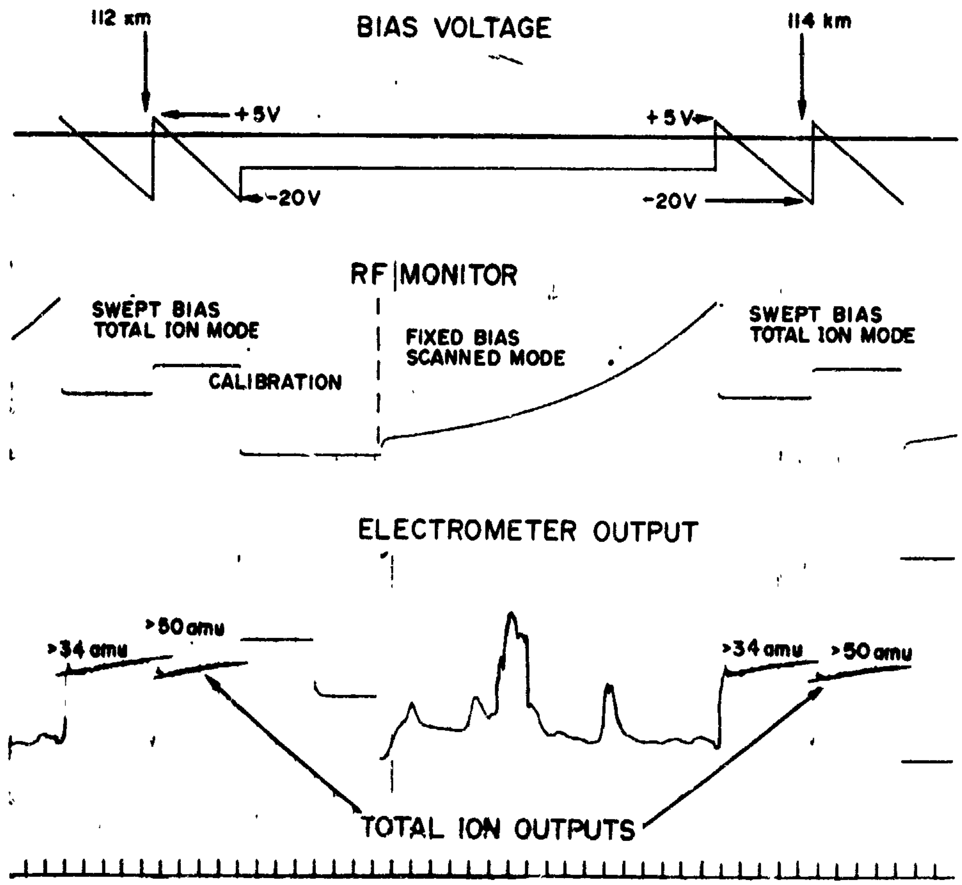

Figure 2. Strip Chart Record Showing Two Characteristics With Smoothing Curves Drawn In

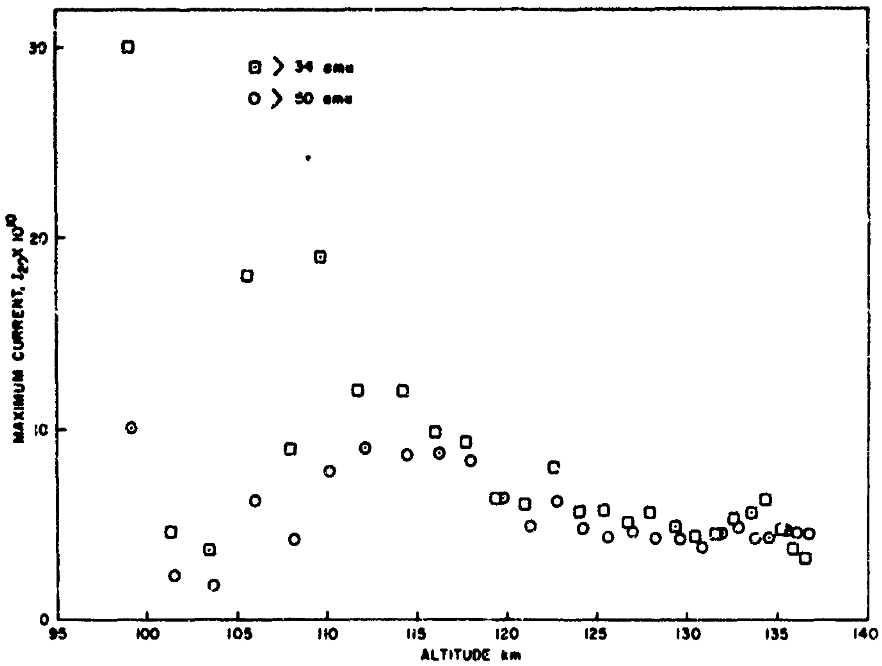

Figure 3. Maximum Current Versus Altitude for the Two Total Ion Modes > 34 amu and > 50 amu

The second aspect is an average quadratic least-squares fit, obtained by fitting a quadratic to each set of five points abstracted from the individual characteristics, and then averaging each of the three coefficients of the fits. From the first of these an estimate of the magnitude of the influence of the applied voltage in collecting particles is obtained; from the second a general idea of the functional form of the characteristic curves is obtained.

The procedure used to obtain I_0 is best understood by reference to the recorded characteristic shown in Figure 2. It is seem that the characteristic consists of two portions, a very steeply rising section of short duration and a longer more slowly rising portion; the latter has the smooth curve mentioned above drawn through it, by eye. The intersection of the two portions of the characteristic is taken to be the point corresponding to I_0, the current at zero field. This point clearly cannot be identified with high accuracy, but the accuracy is adequate for the qualitative conclusions to be drawn in this report.

The maximum ratio data, I_{20}/I_0 versus altitude, are presented in Figure 4. The ratio varies monotonically from a low of $\simeq$ 1.6 at 98 km to a high of $\simeq$ 4.8 at 136 km. Below 115 km the I_{20}/I_0 ratio seems to be generally higher for the lower mass, but this may be due to the scatter of data.

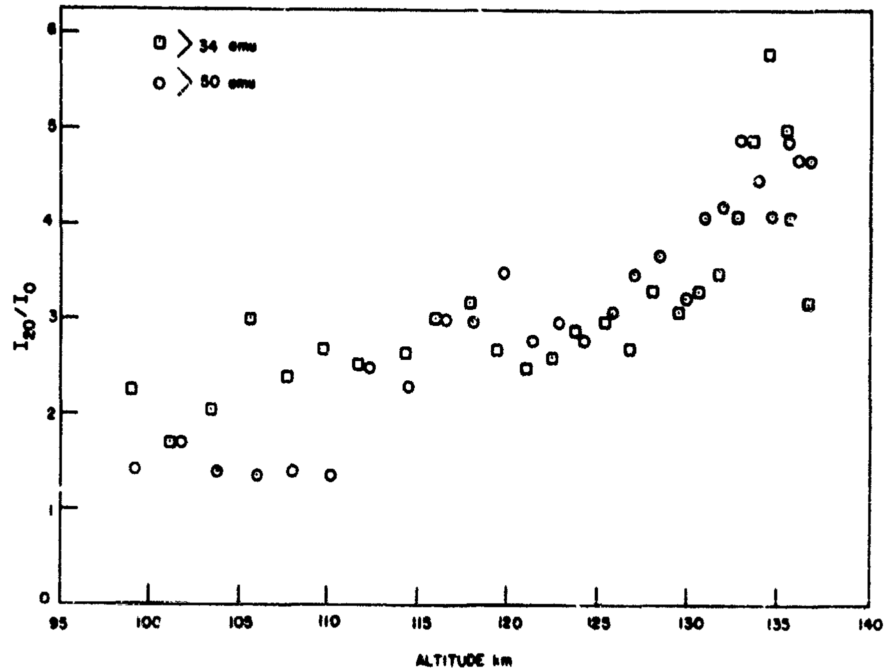

Figure 4. Ratio of Maximum to Field Free Current Versus Altitude for the Two Total Ion Modes > 34 amu and > 50 amu

The averaged coefficients of least-squares fits are

$$C_1 = +2.0154 \times 10^{-10}$$

$$C_2 = +0.2608 + 10^{-10}$$

$$C_3 = -0.001211 \times 10^{-10},$$

and the averaged least-squares fit to the current is, thus,

$$I = 10^{-10}(2.015 + 0.261\ V - 0.00121\ V^2).$$

V, the faceplate voltage with respect to the ambient plasma, has a maximum value of ~ 22 V so that the relative values of the terms at maximum voltage are

2.01 : 5.74 : 0.586.

The linear term still dominates the quadratic term, even at the maximum voltage.

Normally, our instruments are operated at a fixed draw-in potential of -10 V. This draw-in potential is, therefore, of special interest, and a graph of ratios of currents at -10 V bias to field free currents, I_{10}/I_0, is shown in Figure 5.

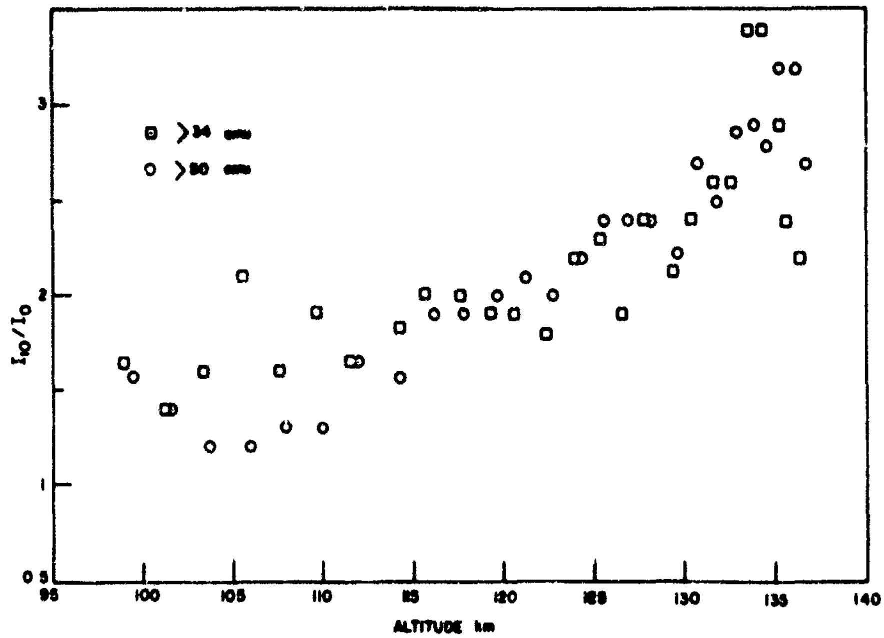

Figure 5. Ratio of Current at -10 V Bias to Field Free Current Versus Altitude for the Two Total Ion Modes > 34 amu and > 50 amu

Further information pertinent to the flight, which may be useful in what follows, is given in Table 1. The first seven rows of the Table are self explanatory; ϕ_0 is the maximum applied voltage (20 V) normalized to the ambient thermal particle energy; s (assumed zero angle of attack) is the ratio of vehicle velocity to mean thermal velocity; and F(s), the field-free ratio of ion collection with forward motion to random (zero vehicle velocity) collection is given by

$$F(s) = \sqrt{\pi}\ s\ (1 + \mathrm{erf}(s)) + e^{-s^2} .$$

The relationship between s and Mach number M is $s = \sqrt{\gamma \pi / 8}\ M$, which for a diatomic gas becomes $s = 0.742\ M$.

Table 1. Useful Flight Parameters

ALT (km)	100	110	120	130	135	Source of Data*
Neutral MFP λ (m)	0.21	1.4	5.4	13.5	19.3	SA
Ambient temp. T (°K)	200	290	480	670	770	SA
Ambient particle velocity (m/sec)	380	460	590	700	750	SA
Vehicle velocity (m/sec)	880	770	640	470	360	FD
Mach No. (m)	3.13	2.25	1.45	0.90	0.65	FD
Ambient charged part. dens. (1/cm^3)	4×10^4	3×10^5	7×10^5	2×10^5	1×10^5	FD
Non-dimensional potential ϕ_o	1160	800	480	350	300	FD, SA
Deby length (cm)	0.49	0.215	0.18	0.40	0.61	FD, SA
s	2.32	1.67	1.08	0.67	0.48	FD, SA
F(s)	8.1	6.0	4.0	2.7	2.1	FD, SA

*SA = Standard Atmosphere
FD = Flight Data

3. THEORY

Details of Parker's (1970) calculations are contained in the reference. Here, only information that is essential for making comparisons with the flight data is presented.

The orifice plate and rocket body are assumed to have the form of a semi-infinite cylinder, with the end cap (orifice plate) having a potential different from the rest of the cylinder.

The following physical conditions are assumed:

Temperature: 0.05 eV or approx. 500°K

Plate potential: 10 V

Dimensionless plate potential: 10/0.05 = 200

Plasma density: 10^4 electrons/cm^3
Debye length: 1.5 cm
Rocket radius: 7.5 cm
Ion Mach number: 1.0 (axial drift toward plate)
Mean free path: $\gtrsim$ 1 m.

Since the mean free path is large compared with other lengths, the problem is considered to be collisionless. The direction of the mean velocity of the ions (that is, the drift velocity of the Maxwellian distribution) is assumed to be along the instrument axis, and the rocket is assumed to be at zero potential relative to the plasma. The orifice is assumed to be so small that the current density at the center of the plate would be the same if there were no orifice, and the current collected is assumed to be equal to the orifice area multiplied by this current density.

The essential results of the calculations are shown in Figure 6, which is reproduced from Parker's report. In addition to the two points for λ_D = 1.5 cm, complete characteristics were calculated for $0 < \phi_o < 200$ for the space charge free (LaPlace) case. There are several points to be noted: (1) For all four cases (M = 0 and 1, λ_D = 1.5 and ∞) the dimensionless current density at ϕ_o = 200 is over 100. (2) The linear form of the characteristics shown by the LaPlace solutions seems to be a very prevalent result of calculations of this type. (3) The reduction in current in going from $\lambda_D = \infty$ (LaPlace) to λ_D = 1.5 cm at ϕ_o = 200 is only a few percent for M = 0, and less than a factor of 2 for M = 1.

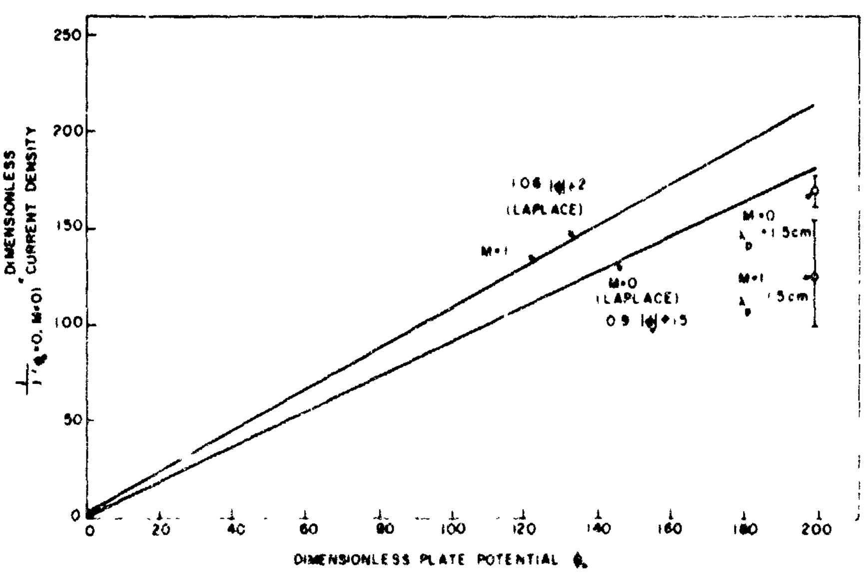

Figure 6 Calculated Current-Voltage Characteristics Showing Complete Characteristics for $\lambda_D = \infty$ and ϕ_o = 200 Points for λ_D = 1.5 cm (after Parker)

4. DISCUSSION

4.1 Comparison of Calculated and Flight Characteristics

Because the calculated and flight characteristics are based on somewhat different physical parameters, these parameters must be scaled before a comparison can be made. The flight characteristics for which physical parameters most closely match those of the calculated values are at 135 km, where the Mach number is 0.65, the ebye length is 0.61 cm, and the potential is 300. As far as scaling the potential is concerned, use may be made of the fact that at higher potentials both calculated and measured characteristics are close to linear. The calculated current values for $\phi_0 = 200$ and $\lambda_D = 1.5$ may also be approximated at Mach 0.65 by a linear interpolation between Mach one ($j = 124$) and Mach zero ($j = 170$). The remaining parameter, which must be adjusted for comparison purposes, is the Debye length. While changing the Debye length from 1.5 to 0.65 cm would decrease the calculated current somewhat, results of the calculations indicate that this change would not be substantial. Furthermore, if the Debye length were playing a critical role in limiting the current, one would expect a substantial change in measured values of i_{20}/I_0 with change in λ_D, between the altitudes of 100 km ($\lambda_D = 0.48$ cm) and 120 km ($\lambda_D = 0.1C$ cm). In fact, instead of decreasing, the measured ratios seem to increase slightly over this altitude range. Thus, neither from the calculations as presently made nor from the measured values of current ratios is one led to expect radical changes in current with changing Debye length. If the difference in Debye length is neglected, the scaled, calculated value of current ratio is then

$$\frac{300}{200}\ [\ (1. - 0.65)\ (170-124) + 124\ ]\ =\ 210.$$

If this value is then renormalized to the total field free collection (that is, divided by $F(s) = 2.1$), one obtains for the adjusted calculated current ratio $\frac{210}{2.1} = 100$. The measured current ratio at 135 km is approximately 5.

The calculated and measured values thus differ by a factor of roughly 20.

The reason for this lack of agreement is not known. The set of simplifying assumptions made in fixing on a model for the calculations might be a contributing factor. A further effect omitted in the calculations is that of the geomagnetic field. Aside from the assumptions made in choosing a model, there is the possibility of a flaw in the calculations that gives erroneous results independently of the correctness of the model conditions assumed. Finally, there is the possibility of an error in the measured characteristics. Although various qualitative arguments may be made, the problem is not well enough understood at the present to allow a definite decision as to which of these factors is responsible for the lack of agreement.

Turning now to the second property that has been chosen as a basis for comparison, namely, the functional form of the characteristic, both measured characteristics and those calculated on the basis of a LaPlace field show a behavior that is roughly linear with ϕ_0 at higher values of ϕ_0. Since the currents obtained from the Poisson field do not differ radically from those obtained from the LaPlace field, this may be used as an argument that there is rough agreement as to functional form.

4.2 Partial Instrument Calibration

The data presented in Figures 4 and 5 offer a means of reducing measured flight currents to equivalent zero-field currents. Thus, the accumulation of such data over a broad range of parameters would constitute an empirical instrument calibration for electric field effects.

4.3 Reduction of Draw-In Potential

The data of Figure 5 show that raising the bias potential from 0 to -10 V results in a rather small gain in amplitude, at most a factor of 3. Since the bias voltages are known, under certain conditions, to cause fragmentation of water cluster ions (see Burke and Miller, 1970; Narcisi, 1970), it might be advantageous to reduce the draw-in potentials used on our positive ion mass spectrometer flights.

4.4 Future Experiments

4.4.1 ADDITIONAL TOTAL ION MODE

A particularly simple extension of the present results would be to include a third total ion mode for ions greater than 20 amu. Since the dominant positive ions at most altitudes are O_2^+ and NO^+, this would be of value in two respects. It would show if further mass discrimination effects are present at higher altitudes, and it would extend the calibration for masses of approximately 30 amu down to lower altitudes.

4.4.2 SCANNED MODE CHARACTERISTICS

The transmission characteristics of the quadrupole are not the same for scanned (mass filter) and total ion modes. Since we are primarily interested in information on specific ions, it would be of interest to operate the quadrupole in the mass filter mode and obtain collection characteristics for specific ions.

4.4.3 COLLECTION FROM WHOLE FRONT END

The measured currents of the characteristics presented in this report were obtained only after transmission of the collected ions through the electric

quadrupole system. It would be of interest to measure the current collected by the whole front end directly, and by comparison see how measured collection characteristics are influenced by the quadrupole transmission characteristics.

Acknowledgments

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